ROADMAP FOR A 400 MHZ CRYOMODULE DEMONSTRATOR AT CERN

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On behalf of the SRF-Development team:
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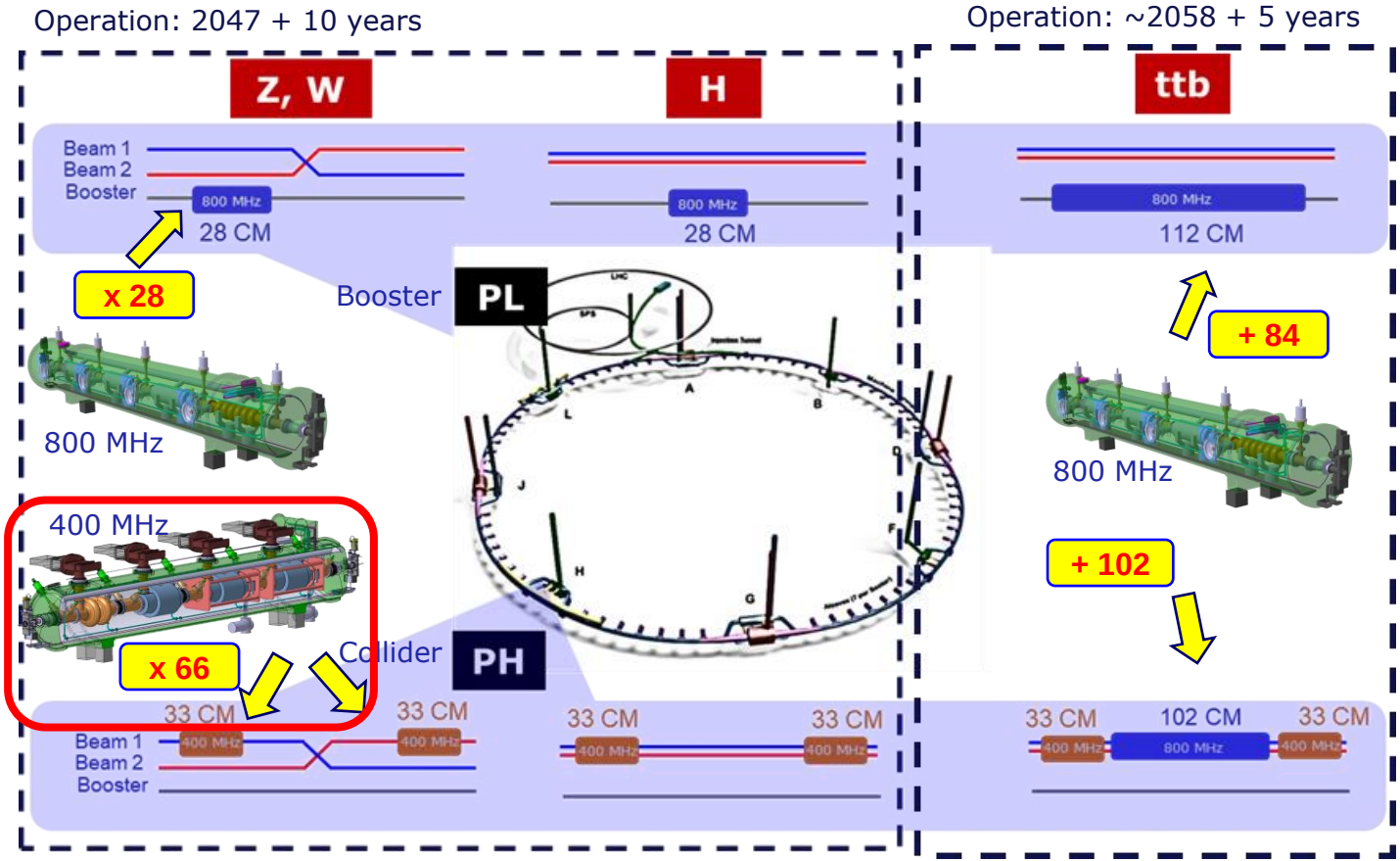
Content

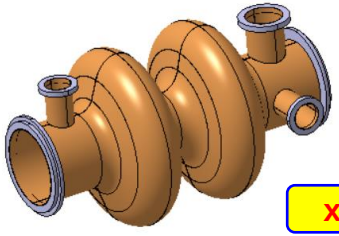
- Where are we coming from ?
- Where are we going ?
- What we want to learn and challenges ahead

Layout of the FCCee SRF system: new baseline (RPO)

Same RF configuration for Z, W, and ZH, extended with additional 800 MHz CM for ttbar (collider and booster)



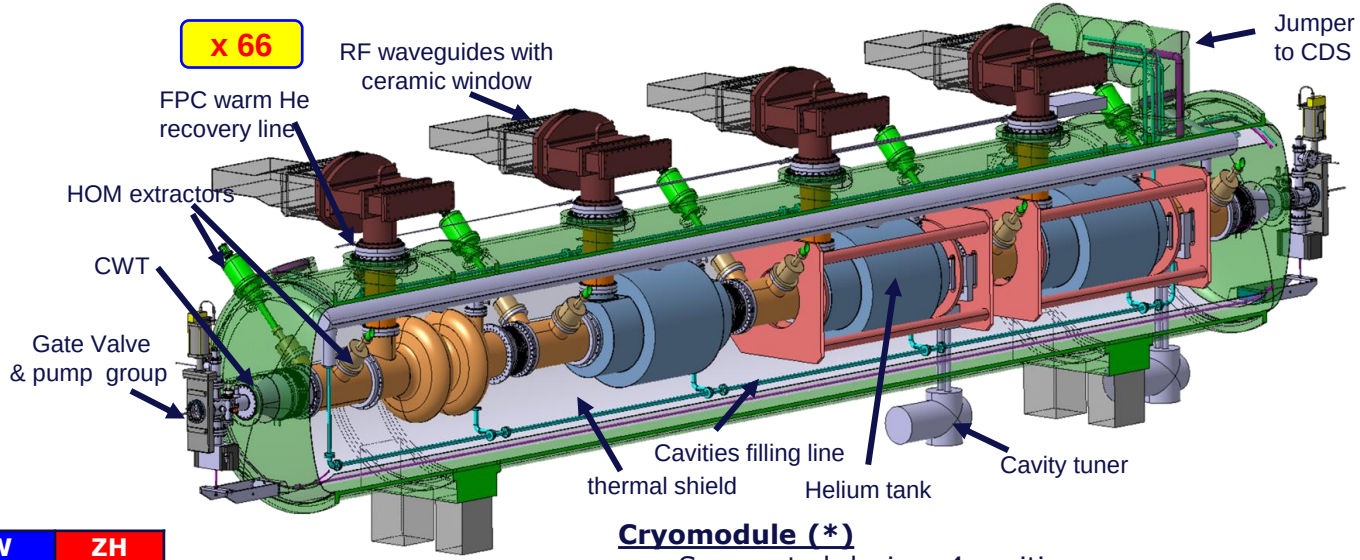
400 MHz system – collider Z, W, ZH



x 264

Superconducting elliptical cavity

- 400 MHz, 2-cell, copper substrate
- Electropolished RF surface
- Niobium sputtered (HiPIMS)



Collider	Z	W	ZH
	1 beam RPO	1 beam	2 beams
Total RF voltage [MV]	89	1049	2098
Beam current [mA]	1283	135	2 x 26.8
RF Frequency [MHz]	400.79		
Operating temp. [K]	4.5		
Cavity voltage [MV]	7.95		
# cell/cavity	2		
Eacc [MV/m]	10.6		
Q0	2.70E+09		
RF power [kW]	380		
Optimum coupling QL	9.2E+05		
# CM (with 4 cav/CM)	66		
# cavities	264		

Cryomodule (*)

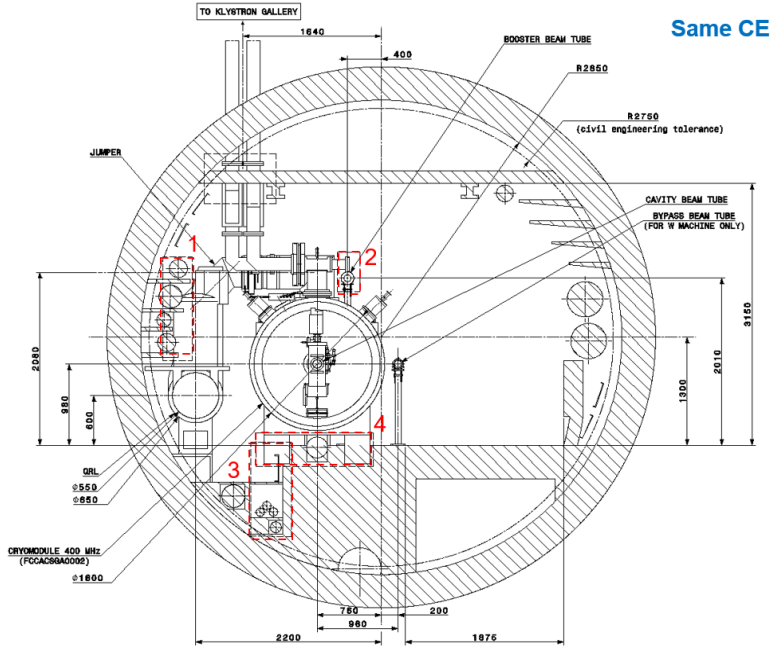
- Segmented design, 4 cavities
- Vertical FPC, HOM damping and extraction
- Frequency tuning system
- Thermal and magnetic shielding

More on CM in talk: K. Canderan, "SRF 400 & 800 MHz cryomodules: design evolution and future work"

FPC in talk: S. Zadeh, "FCC-ee Power Coupler Design Overview", Thurs. 8:45.

* See FCCee Feasibility Study Report (Chapter 3.4.11)

400 MHz CM tunnel integration (pt. H)



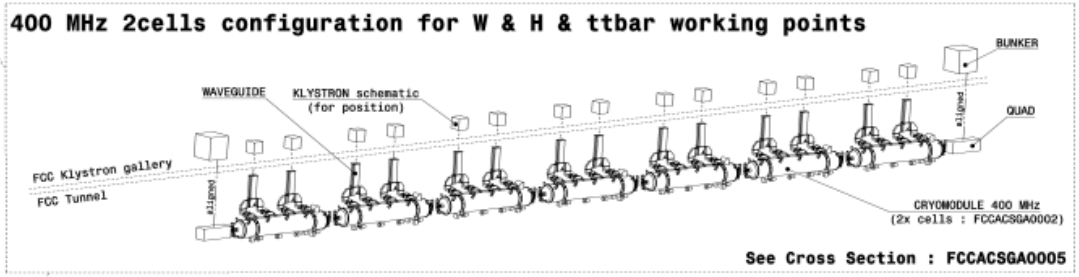
FCCee Feasibility Study Report (Fig. 3.45)

Same CE as arcs

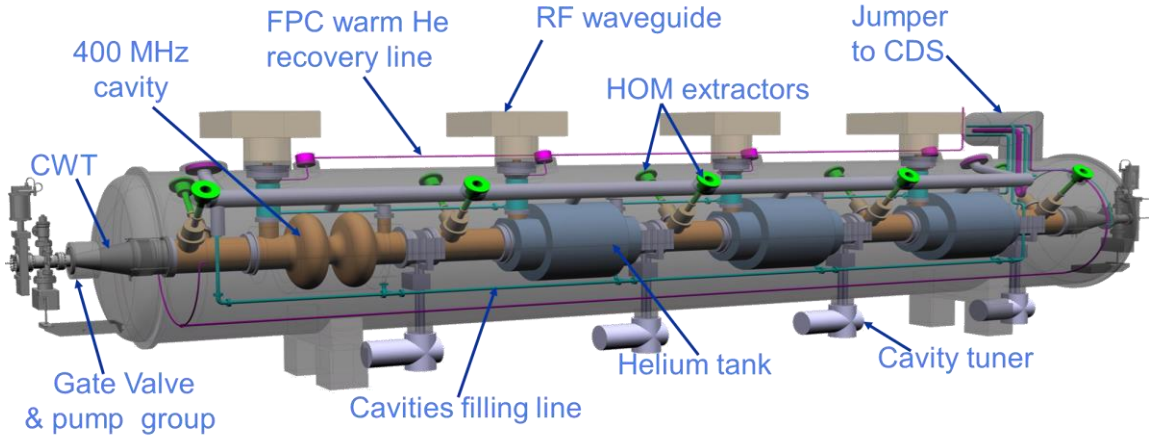
CE from the arcs:
issues still to be addressed in the pre-TDR phase: separation/recombination optics, machine height, some physical interferences, beam height, transport & installation…

→ Pt.H cross section changes underway: cable-trays, reduced fumes extraction needs;
→ CM design evolution towards compactness

More in talk: M. Timmins/F.Valchkova, "RF General Layout and Integration", session on: Technical Infrastructure: RF Points and Cryogenics, Tue.20 May, 10:30.

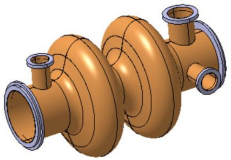


Build 400 MHz Demo, an FCC 2-cell cavity full size cryomodule

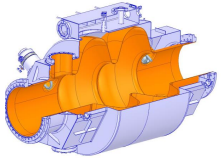


Parameter (machine installed)	Value
No. cryomodules	66
2-cell cavities per cryomodule	4
CM length (GV flange to flange)	~ 11 m
RF frequency (MHz)	400.79
Cavity voltage (MV)	7.95
Cavity gradient Eacc (MV/m)	10.6
Qo	2.7E+09
Dyn. HL (CW)/cavity at 4.5 K	129 W
Stat. HL/CM	197 W
Environ. Magnetic field	≤ 5 mG
RF power (kW, CW)	380
Q_L (optimum coupling)	9.2E+05
HOM power per CM: Z (W/H/ttbar)	62.3 kW (coax. Extractor for 15/20 kW peak!) (lower for W/H/ttbar)

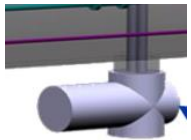
Items to be designed, built and qualified (non exhaustive list!)



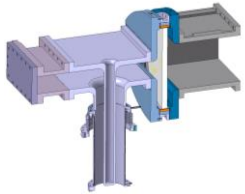
Cavity Nb sputtered



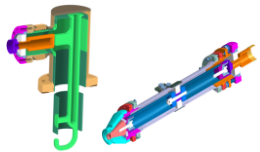
He tank (LHC design shown)/cavity assy



Tuning system



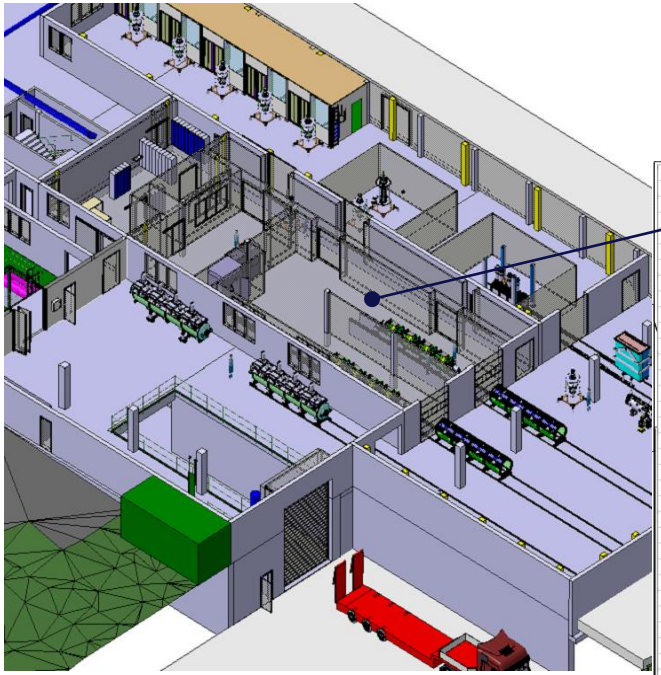
FPC (with WG windows)

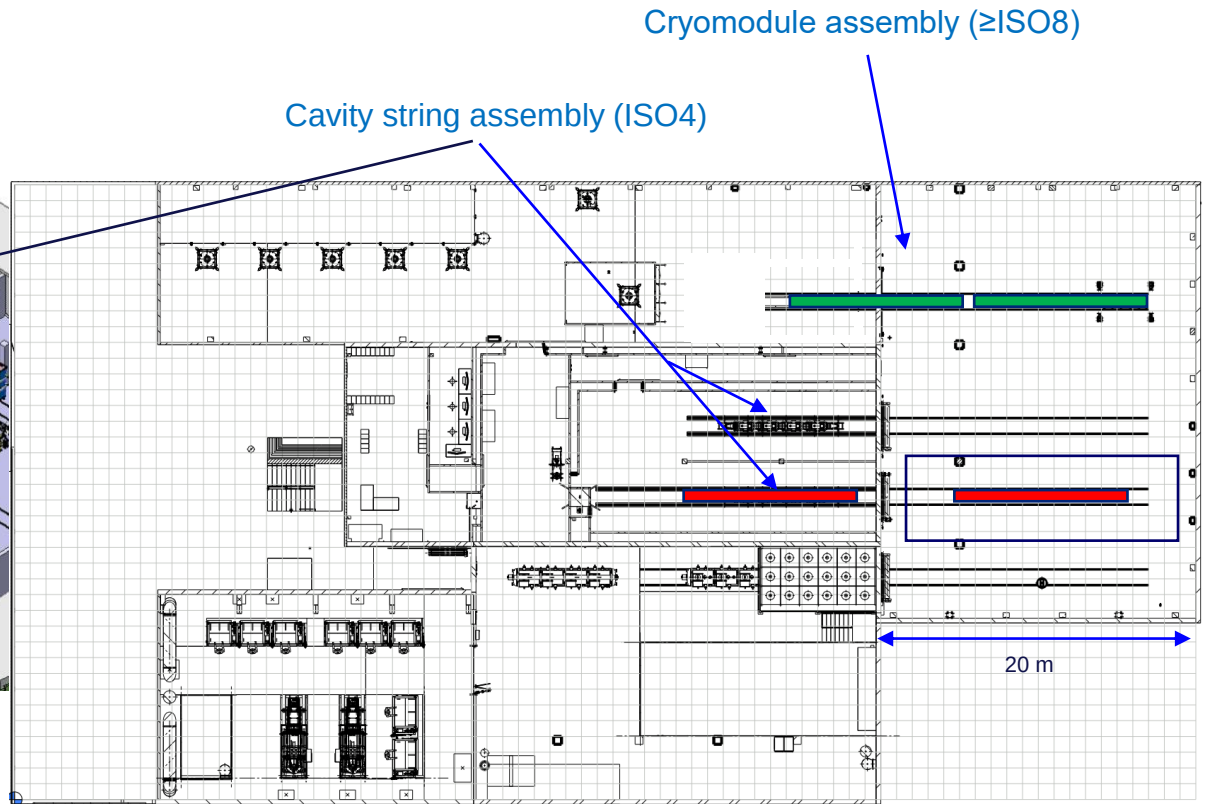


HOMs, RF extraction lines (LHC/Crab designs shown)

Lots of resemblances with LHC CM, but **final designs may be considerably different !**

SA18, new CERN SRF facility (operational 2030)



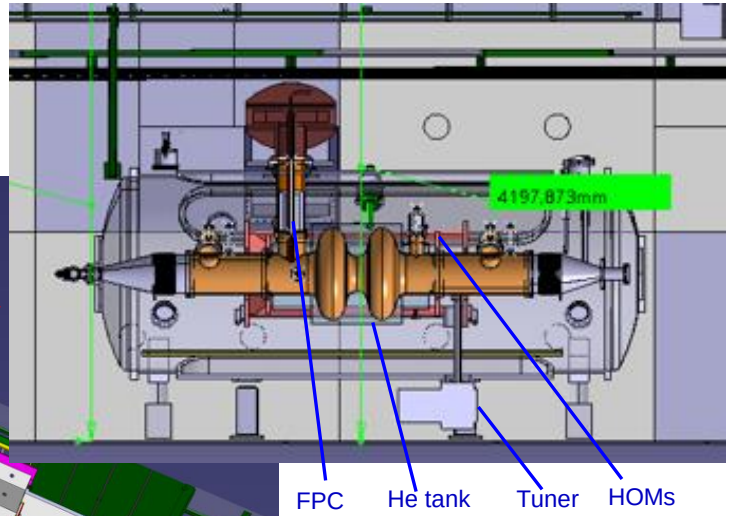


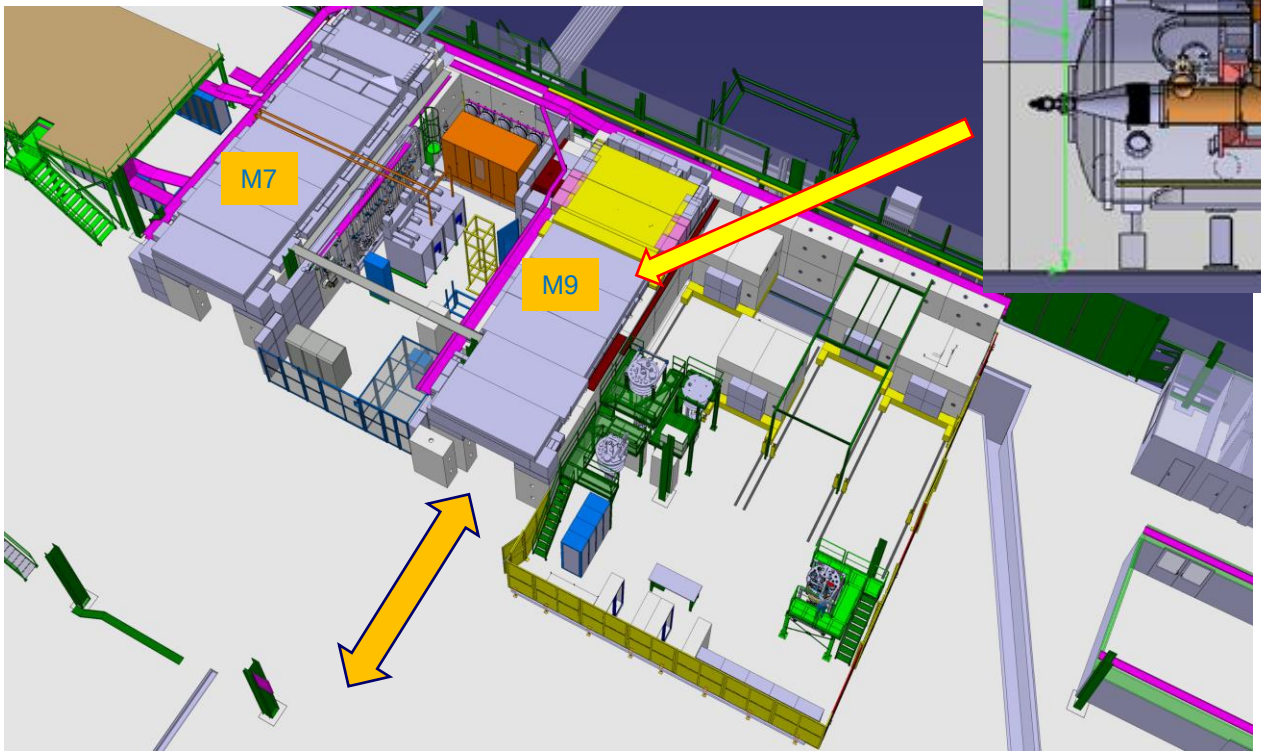
For 400 MHz DEMO CM:

- Engineer, build and install assembly tooling for clean-room and out of CR cryomodule assembly
- Set-up all specific test tools and qualification instrumentation

Build Horizontal Test Cryostat (HTC) in SM18 test bunker M9

- Full power test of a fully “dressed” cavity: He tank/tuner/HOMs/FPC
- Multi-purpose test station (for a variety of cavities/FPCs)
- Operation temperature: from 4.5 K down to <2 K





Objectives of 400 MHz DEMO

Incremental learning

Training of a new generation of scientists/engineers/technicians on SRF related technologies:

- SRF, mech.engineering, surface coating, cryogenics, etc.

Develop technologies:

- Mechanical fabrication of 2-cell cavities (5 ports) according to specs
- Coating (Nb sputtering on Cu) technology (HiPIMS) to reach the required gradient and Q_0-values
- Development EP (promising to improve performance, or other surface treatment, what are the specs?)
- Control of field emission (cleanliness protocols during assembly) to reach required gradient

Component specific objectives:

- Cavity performance goals (gradient/Q_0) from vertical test to CM installed
- FPCs: electrical/mechanical design & construction to demonstrate full power test objectives in HTC tests (380 kW CW, 500 kW peak)
- HOMs: electrical/mechanical design & construction for 1-7 kW range RF power extraction
- Cavity tuning needs → design & construction of tuning system and helium tank

Cryomodule objectives:

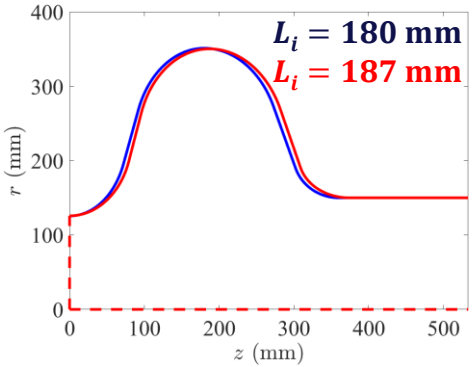
- CM integration of SRF systems and other systems (cryo, vacuum,etc.)
- CM design & construction: magnetic shielding(s), supporting systems, vacuum tank, thermal shielding.→ CM size !
- CM assembly procedures: ISO4 cavity string assy, cryostat assembly and tools/quality controls
- Understand complexity in view of series production
- CM thermal performance → multi-cavity SRF operation, fast CD, cryogenic thermal performance

Building new SRF test facilities:

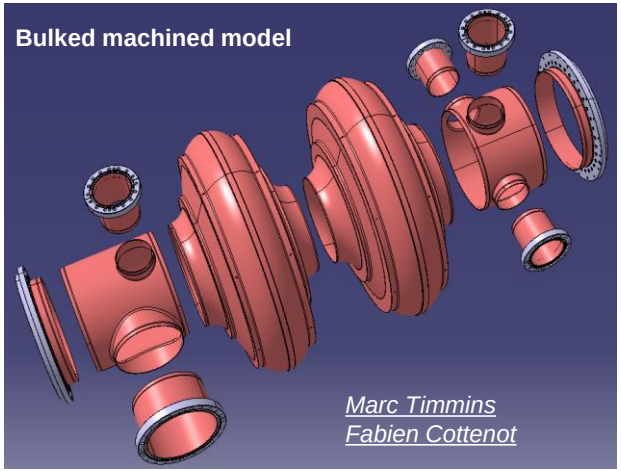
- Horizontal Test Cryostat (HTC) for full-power test on « dressed cavity » assemblies

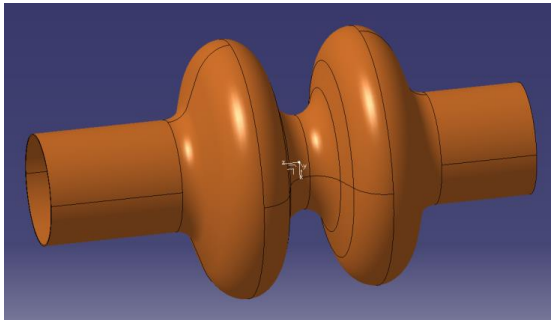
2-cell 400 MHz cavity shape

- **Initial Cavity Optimization**: Shape optimized to minimize peak longitudinal impedance of HOMs and $B_{\mathrm{pk}}/E_{\mathrm{acc}}$, with $E_{\mathrm{pk}}/E_{\mathrm{acc}}$ kept low
- **5 ports:** 1 Port for FPC, two ports for HOM couplers, 1 port for pick up antenna and one port for possible use of Fast Reactive Tuning (FRT)



$L_i = L_e$ [mm]	R_{eq} [mm]	R/Q_π [Ω]	R/Q_0 [Ω]
187	350.190	181.1	0.63
180	351.041	182.7	0.004
$L_i = L_e$ [mm]	G [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]
187	234.7	2.0	5.33
180	232.7	2.0	5.33





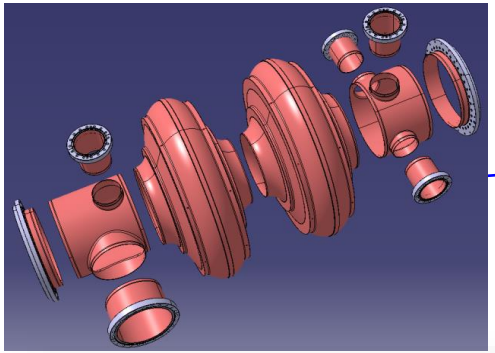
More in next talk: S. Zadeh, "Accelerating cavities with HOM damping for FCC-ee"

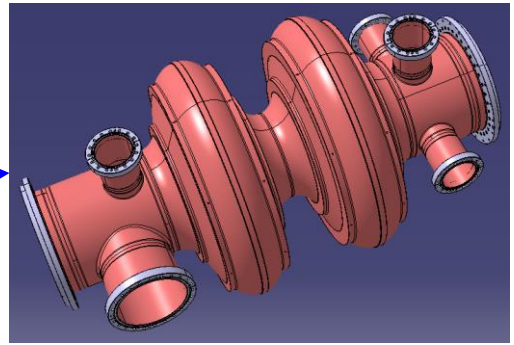
Bulk machined cavity (the “perfect” substrate)

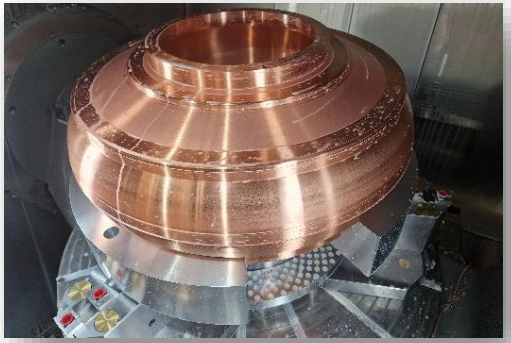
Bulk machined cavity for coating qualification

→ initial thickness (~4 mm) with reduction budgets for chemistry

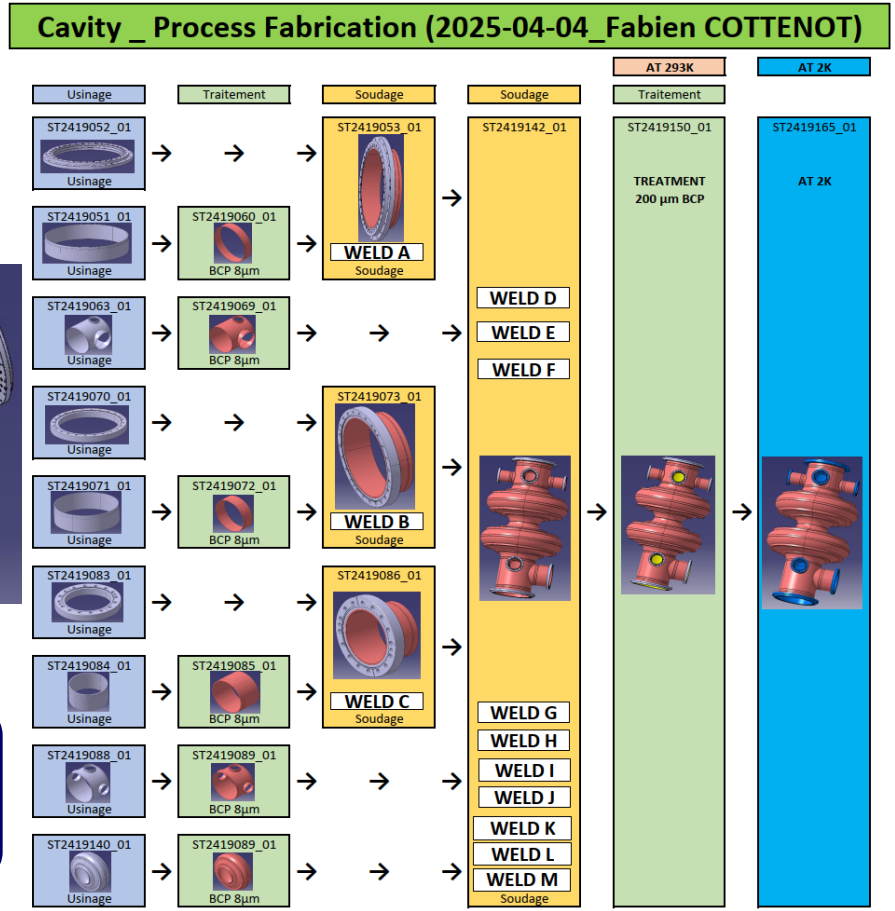
→ Welding fabrication steps





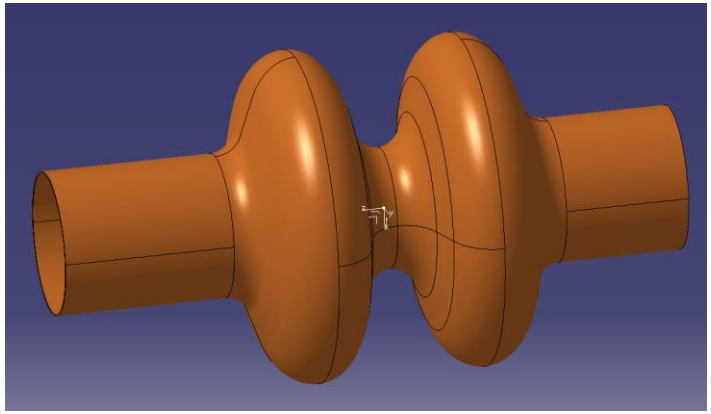


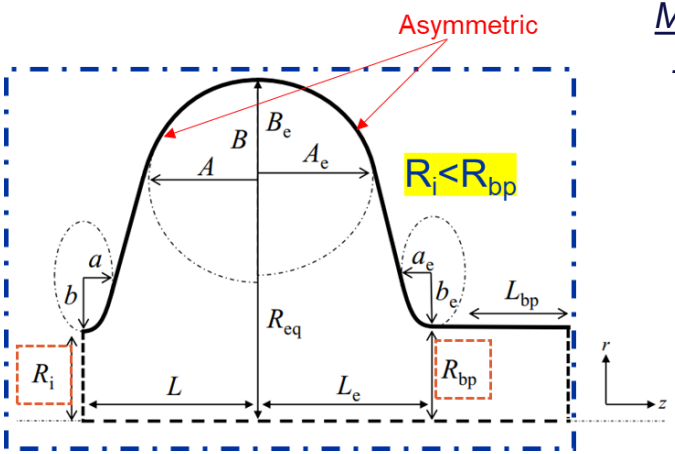
More in talk: M. Garlasche, “Cavity substrate development”, session: SRF: technology, Wed.21 May, 11:00



(M. Timmins, F. Cottenot)

Hydroforming



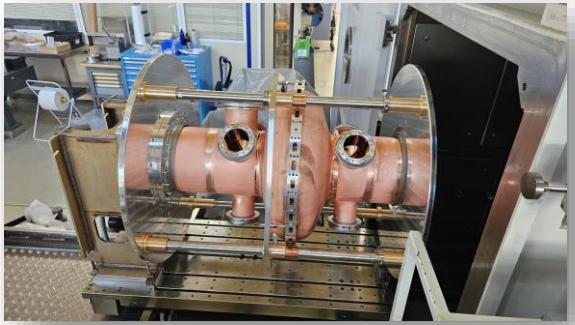


Multi-step Hydroforming
1.3 GHZ KEK –CERN

Current FCC Design:

- Challenging asymmetry and ratios
- Study ongoing with industry (DE)
- Is a hydroformed single-piece achievable?
- Single cells then iris welding ? Avoid inner equatorial weld
- Industrialization cost effectiveness to be studied (264 cavities in ~ 3 yrs ?)

More in talk: M. Garlasche, "Cavity substrate development", session: SRF: technology, Wed.21 May, 11:00



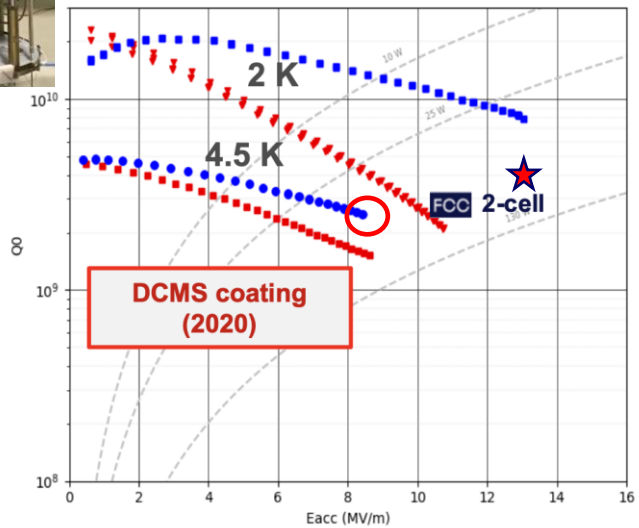
LHC welded cavity

400 MHz 2-cell Nb/Cu (thin film sputtering)

What we have today:

- Single-cell LHC bare cavity, no ports:
  - ✓ $Q_0 = \sim 2.2 \times 10^9$ at $E_{acc} = \sim 8.2$ MV/m

HIPIMS coating + High Pressure Water Rinsing + Nb coated flanges (2023)



We need to demonstrate (goals):

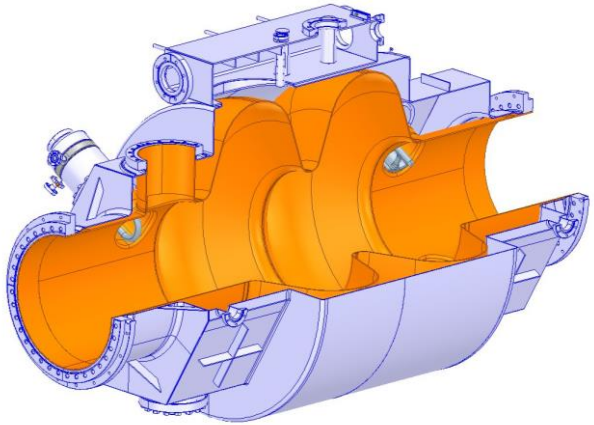
- Bare cavity, vertical test (2-cell FCC shape with ports):
  - ✓ $Q_0 = 3.3 \times 10^9$ at $E_{acc} = 13.2$ MV/m for 2-cell 400 MHz Nb/Cu
- Dressed cavity (with FPC, HOM) on horizontal test (HTC):
  - ✓ $Q_0 = 3.0 \times 10^9$, $E_{acc} = 11.8$ MV/m
- Tested in CM (accelerator goals):
  - $Q_0 = 2.7 \times 10^9$, $E_{acc} = 10.6$ MV/m
- Surface preparation 400 MHz Nb/Cu:
  - ✓ HiPIMS has shown promising results on several 1.3 GHz single-cell cavities[1].
- Cavity manufacturing:
  - ✓ enhance copper substrates → seamless cavities using bulk machining, and/or hydroforming technologies

Talk SRF R&D: W. Venturini, "Strategy for SRF R&D at CERN", session: SRF: technology, *Wed.21 May, 10:45*

Talk on EP: L. Ferreira, "Electropolishing of large copper substrates for FCC_ee SRF cavities", session: SRF: technology , *Wed.21 May, 11:15*

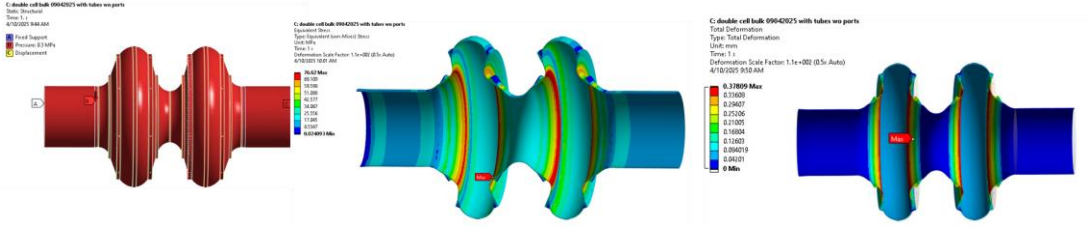
1. L. Vega Cid, R&D on superconducting thin films for SRF cavities, RF seminar, 2024, CERN

Cavity, helium tanks, tuning needs



Preliminary concept (LHC based)

Double cell ST2419142 040425, ports removed, tubes 3.84 thickness

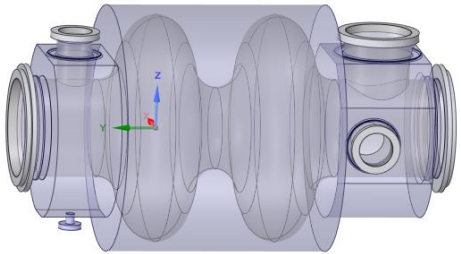


(K.Artoos et al.)

Perform simulations to determine the thickness of the cavity and the He tank. Influencing parameters:

1. Pressure
2. LFD and PS
3. Tuner type

lations on stiffness with He tank, tuning forces



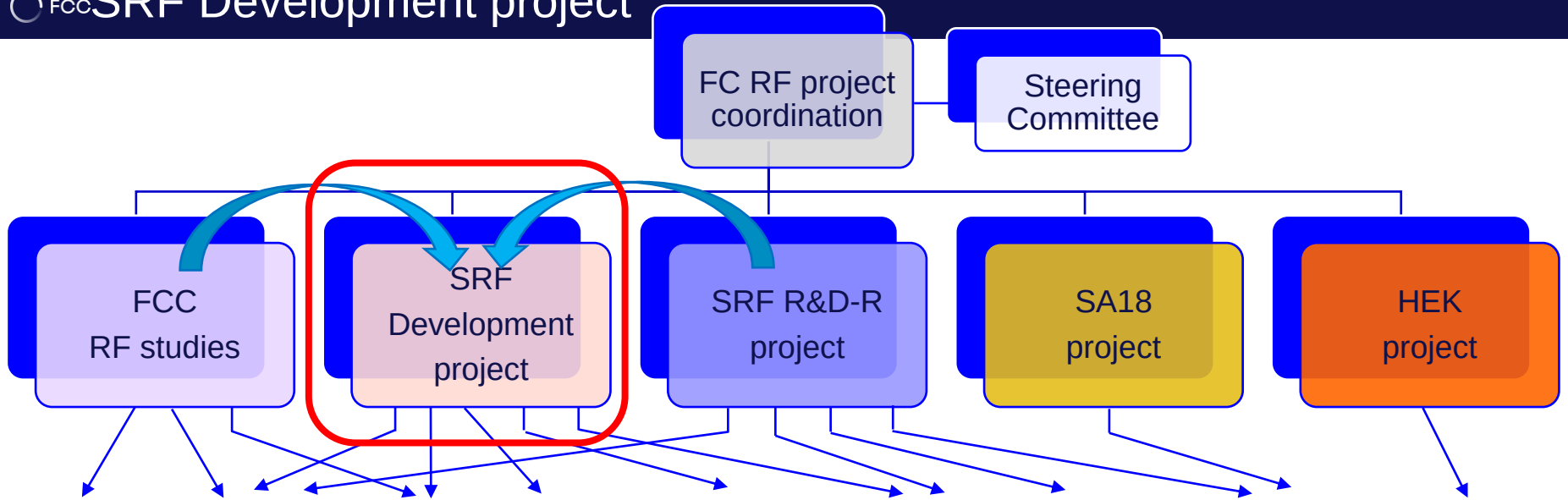
(T. Hernandez, EN-MME)

CAVITY			
Thickness [mm]	Force [KN]	Displacement [mm]	Stiffness [KN/mm]
2.5	1	0.11	9.51
2.75	1	0.09	10.63
3	1	0.08	11.77
3.25	1	0.08	12.95
3.5	1	0.07	14.15
3.75	1	0.07	15.38
4	1	0.06	16.64

Thickness [mm]	2.5	2.75	3.0	3.25	3.5	3.75	4.0
Cavity Stiffness Kcav [kN/mm]	9.5	10.5	11.6	12.7	13.9	15.0	16.2

(Shahnam Gorgi Zadeh, SY-RF)

FCC SRF Development project

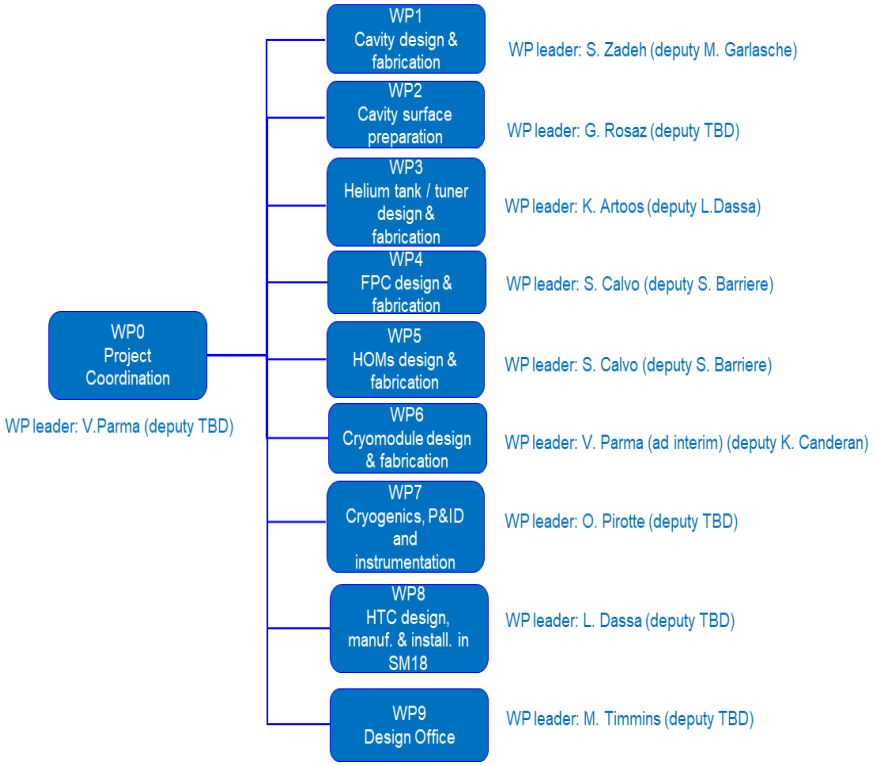


Pole 0 (RF)	Pole 1 (MME)	Pole 2 (RF,MME,CRG,VSC)	Pole 3 (RF, CRG,MME)	Pole 4 (RF)	Pole 5 (VSC)	Pole 6 (RF)	Pole 7 (RF, VSC)	Pole 8 (RF)
• RF parameters and design • Beam dynamics studies	• Cavity mechanical design and manufacturing	•Cryomodule design and construction •HTC	• SM18 SRF test infrastructure	• FPC and HOM	• Cavity surface preparation • Cavity coating • SRF thin films	• Non mechanical tuning	• SRF infrastructure • SA18 equipment	• High power RF systems

Poles of technologies and competencies

Mech. Eng. & Manufacturing, Vacuum, Cryogenics and other Groups, a CERN Accelerator Sector endeavor !

SRF Development Project Team



~ 15 people today

The team is growing ! We‘re hiring !

17 new Staff Positions (5 yrs, onboarding ‘25-’27): 85 FTE.y

- ✓ 8 posts in SY-RF (Radio-frequency);
- ✓ 5 in EN-MME (Mechanical & materials engineering);
- ✓ 3 in TE-VSC (Vacuum, surfaces & coatings);
- ✓ 1 in TE-CRG (Cryogenics);

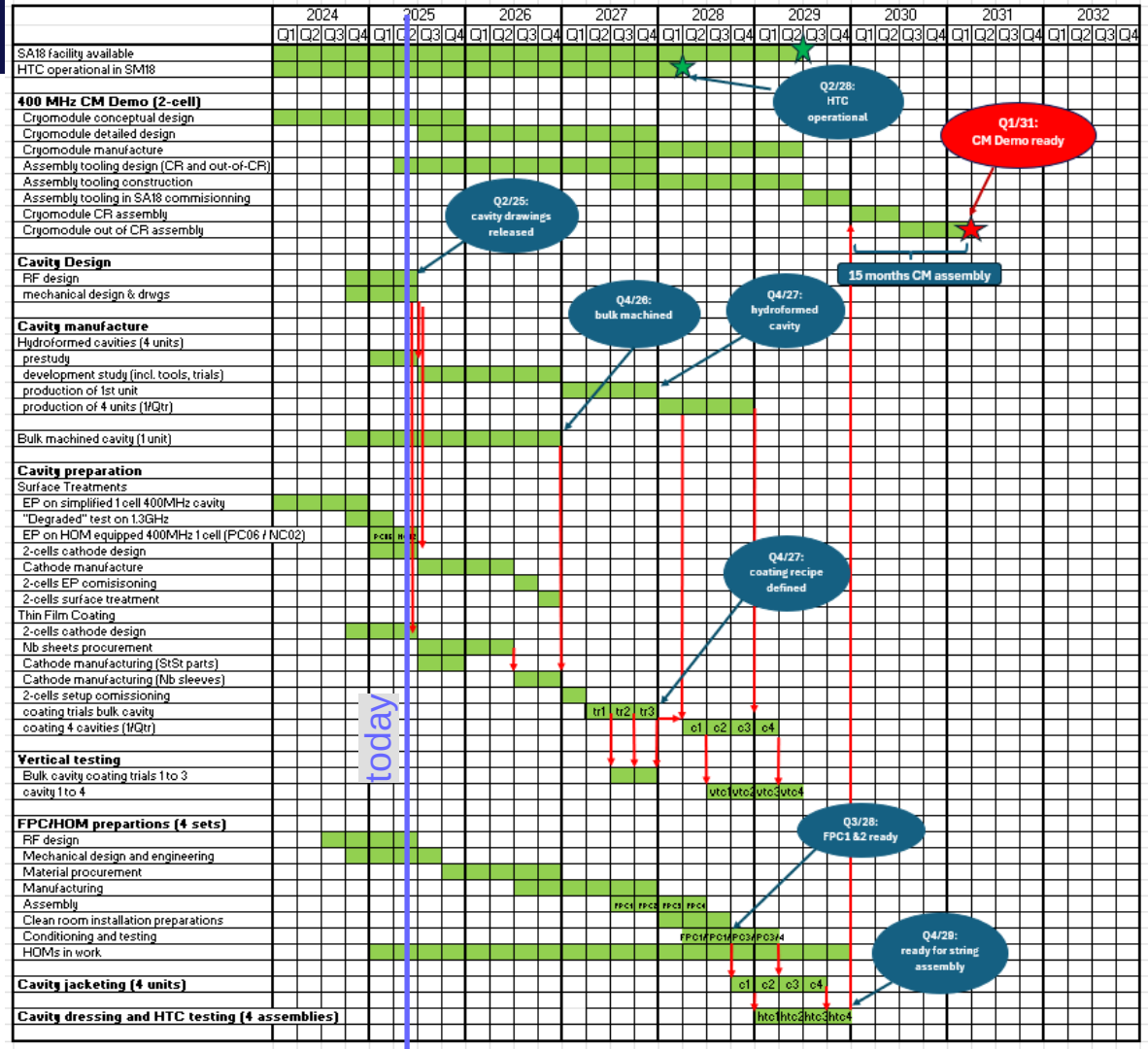
Status of hiring:

- ✓ Hired: 3 (1 in SY-RF; 1 in EN-MME; 1 in TE-VSC;); 1 select.board in prep. (EN-MME)
- ✓ Positions to be published:
  - 1 in 2025 (1 in SY-RF)
  - 4 in 2026 (2 in SY-RF; 1 in TE-CRG; 1 (tech.) in EN-MME)
  - 8 in 2027 (1 in SY-RF; 3 (tech) in SY-RF; 1 in EN-MME; 1 (tech.) in EN-MME; 1 in TE-VSC; 1 (tech.) in TE-VSC);

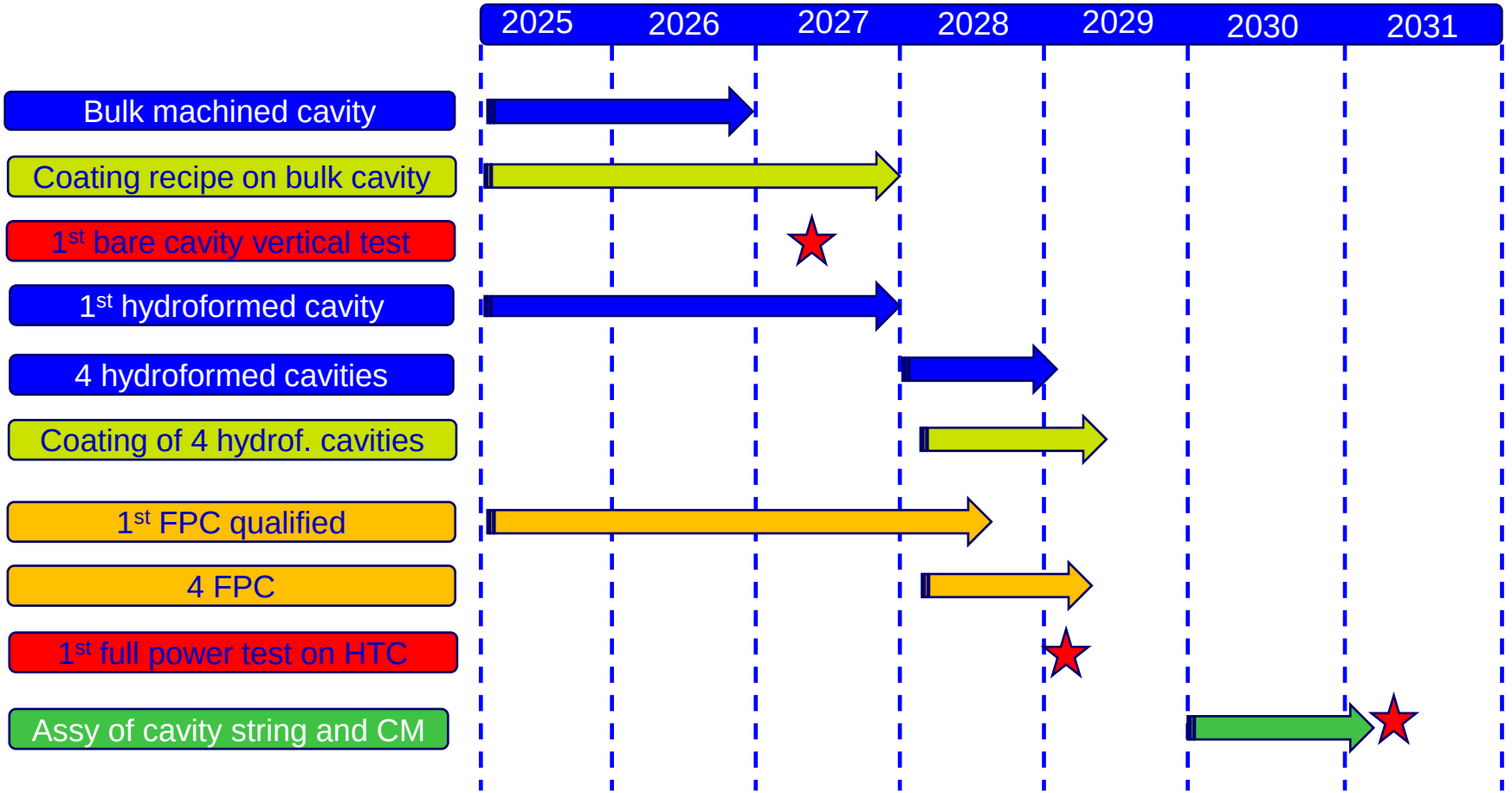
18 new Graduate positions: in 2025-2031, first 3 to join 2nd half 2025

Interested? https://careers.smartrecruiters.com/CERN/

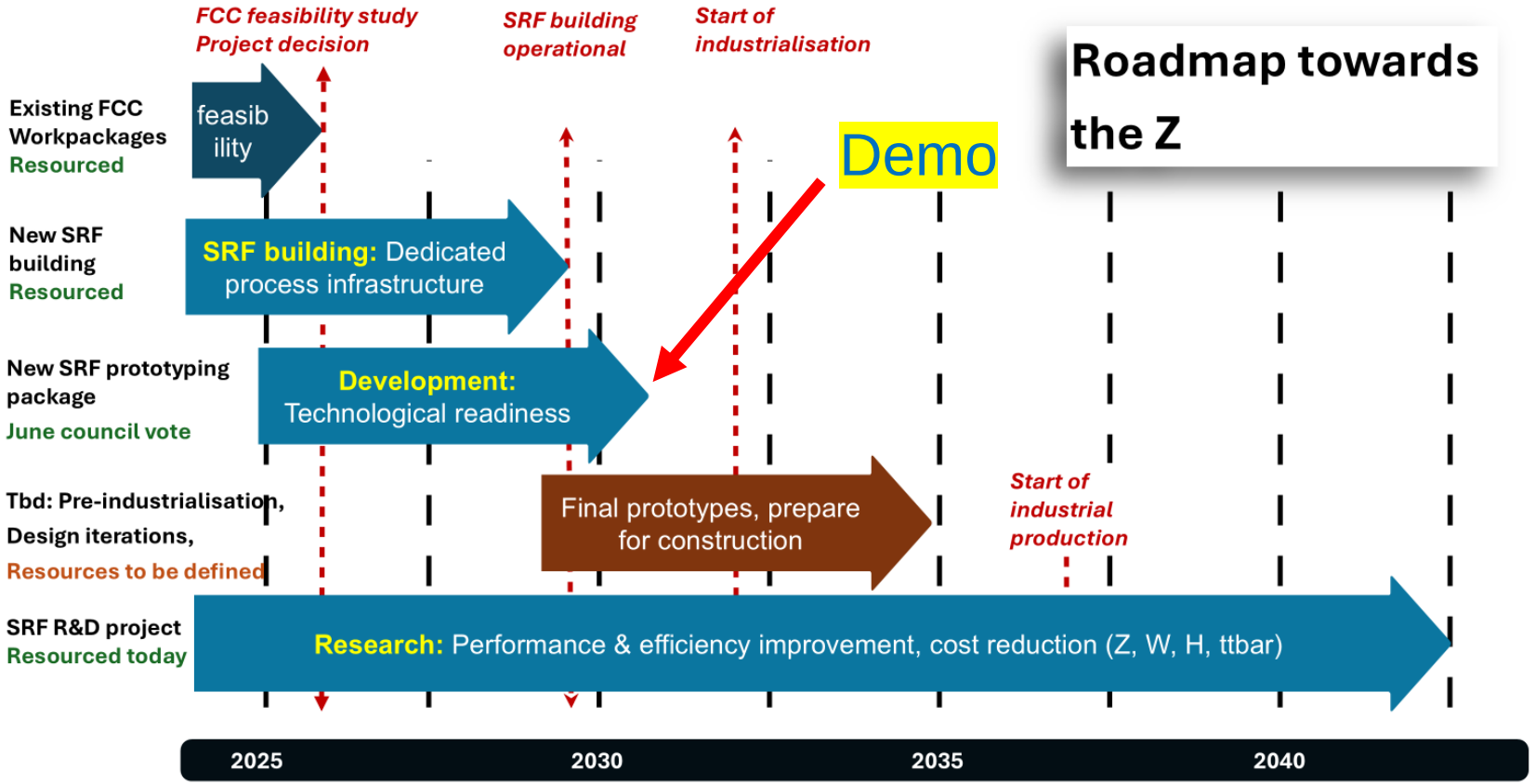
Master schedule



Simplified schedule



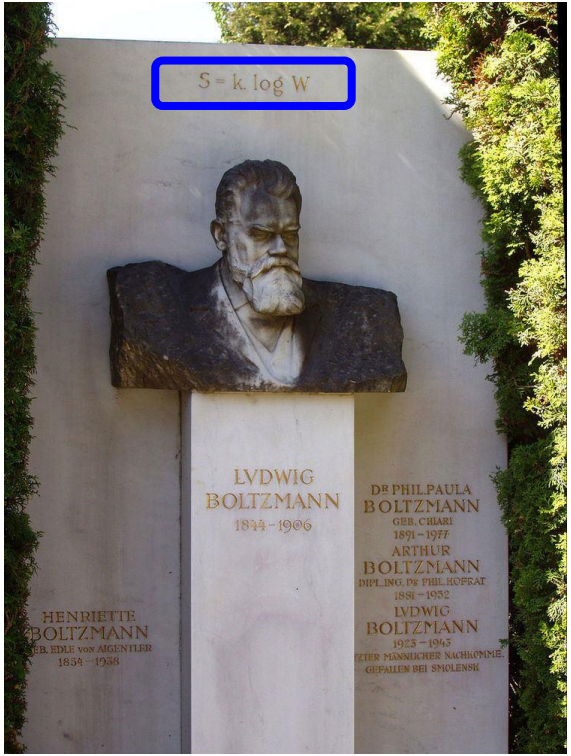
Outlook beyond Demo



Summary

- Conceptual design of 400 MHz CM completed and documented in the FCCee Feasibility Study Report
- We now aim at building a 400 MHz DEMOnstrator Cryomodule by 2031 while achieving key SRF technology results (cavity/FPC performance) by 2028
- We plan to train a new generation on SRF technologies
- An ambitious program we need to remain focused, and also need continuous support from CERN's management
- We are calling for a review of our SRF program for FCC with external experts on 7-10 October next

Wiener Zentralfriedhof



"Bring forward what is true.
Write it so that it is clear.
Defend it to your last breath."

For a thorogh account of Boltzmann's life and scientific influence:
Carlo Cercignani: " Ludwig Boltzmann: The man who trusted atoms", Oxford University Press, ISBN 0198501544

FCC

Thank you
for your attention.